# HUMAN IMPACTS TO RIVER TEMPERATURE AND THEIR EFFECTS ON BIOLOGICAL PROCESSES: A QUANTITATIVE SYNTHESIS[1]

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ABSTRACT: Land-use change and water resources management increasingly impact stream and river temperatures and therefore aquatic organisms. Efforts at thermal mitigation are expected to grow in future decades. Yet the biological consequences of both human thermal impacts and proposed mitigation options are poorly quantified. This study provides such context for river thermal management in two ways. First, we summarize the full spectrum of human thermal impacts to help thermal managers consider the relative magnitudes of all impacts and mitigation options. Second, we synthesize biological sensitivity to river temperature shifts using thermal performance curves, which relate organism-level biological processes to temperature. This approach supplements the popular use of thermal thresholds by directly estimating the impact of temperature shifts on the rates of key biological processes (e.g., growth). Our results quantify a diverse array of human thermal impacts, revealing that human actions tend to increase more than decrease river temperatures. Our results also provide a practical framework in which to quantify the sensitivity of river organisms to such impacts and related mitigation options. Finally, among the data and studies we synthesized, river organisms appear to be more sensitive to temperature above than below their thermal maxima, and fish are more sensitive to temperature change than invertebrates.

(KEY TERMS: climate change; global warming; stream ecology; river ecology; thermal; mitigation; fish; invertebrate.)

## INTRODUCTION

Temperature is the single most important environmental condition affecting the lives of organisms (Brown et al., 2004; Begon et al., 2006; Clarke, 2006). Most aquatic organisms are ectotherms, whose body temperature fluctuates directly with ambient water temperature (Giller and Malmqvist, 1998). Ecto-therms are adapted to the spatial and temporal temperature patterns experienced in their native ranges (Huey and Kingsolver, 1989; Hill et al., 2004; Begon et al., 2006; Lomolino et al., 2006) and are sensitive to environmental temperature change (Sweeney and Vannote, 1978; Walther et al., 2002).

Humans have profoundly altered river temperatures via dams and diversions, deforestation, urbanization, and channelization, all in addition to the

projected impacts of climate change (Poole and Berman, 2001; Caissie, 2006). This occurs both by altering the heat fluxes to and from the waterway and by altering the amount of water flowing in the channel upon which those heat fluxes act (Webb, 1996). It is well established that such thermal impacts can affect aquatic organisms, often deleteriously (Smith, 1972; Bear et al., 2007; Carveth et al., 2007). Recognition of such impacts by regulatory agencies is recent, and has led to placing water bodies in many states on the Clean Water Act 303 (d) list as water quality impaired for temperature (e.g., Oregon Department of Environmental Quality, 2006; Kentucky Environmental and Public Protection Cabinet, 2008). These listings will ultimately lead to the development of Total Maximum Daily Loads (TMDLs) for temperature, such as that for the Willamette River in Oregon, which apportion excess thermal loads to specific sources in the watershed. Thermal mitigation efforts are even more in their infancy, yet such activities will only become more important and more common as human activities and climate change accelerate in the 21st Century. An approach to environmental mitigation that is gaining popularity is market-based trading programs (e.g., BenDor et al., 2009). This approach is already being applied to address thermal impairment quantified in the Willamette River TMDL (Hulse et al., 2007; Rounds, 2007) and similar programs will likely develop elsewhere. All such thermal mitigation approaches will need to be able to quantify human impacts to temperature, the thermal impacts of mitigation, and the biological implications of both.

Determining the expected impact of temperature changes, whether natural or anthropogenic, on aquatic organisms is challenging. Decision makers must somehow make sense of the scientific literature on the thermal biology of aquatic organisms, which is extensive and sometimes complicated, particularly for fish. This array of information must be reduced to basic principles and datasets that can be employed in practical ways. Thermal tolerance limits are a common approach, where biological processes like growth or reproduction, or even survival itself, are expected to decline or cease beyond a certain temperature (Eaton et al., 1995). Alternatively, such limits can be viewed behaviorally as temperatures beyond which organisms avoid (Coutant, 1977). Such thresholds are an important component of organism response, and can anticipate organism response to temperature change in a basic way, but do not fully capture the impact of temperature change on biological process rates.

The effects of temperature change on organism-level biological processes (e.g., growth) are more fully characterized by thermal performance curves that relate process rates to temperature (Cossins and Bowler, 1987). Thermal performance curves exhibit a
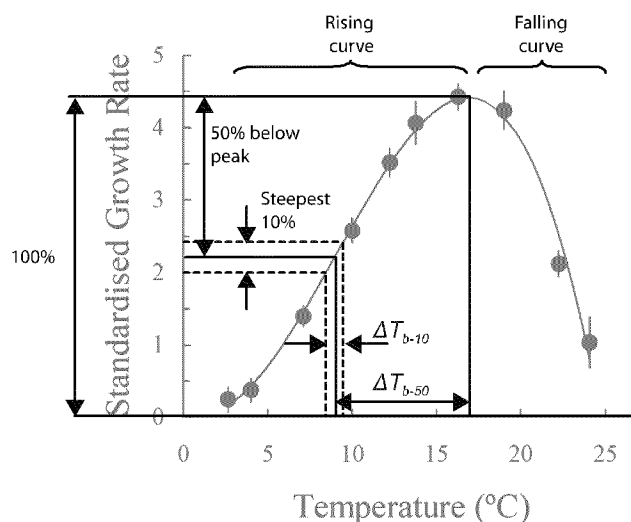


FIGURE 1. Example Thermal Performance Curve Showing Rising/Falling Portions of Curve. Example calculation of $DT_{b-50}$ (=8$_7$C) and $DT_{b-10}$ (=1.2$_7$C) for rising portion also shown; calculation for falling portion is analogous but not shown. Growth rate plot reprinted from Ojanguren et al. (2001), with permission from Elsevier.

humped shape, with minimum and maximum temperatures outside which the process ceases, and an optimum temperature associated with the maximum process rate (Figure 1) (Huey and Kingsolver, 1989; Begon et al., 2006). A wide array of thermal performance curves for stream and river species have been published in the scientific literature (e.g., Hokanson et al., 1977; Ojanguren et al., 2001; Billman et al., 2006), but these data have never been compiled to consider their utility in evaluating the sensitivity of aquatic organisms to temperature change or considering thermal mitigation options. In addition, although significant reviews have cataloged a variety of human impacts to stream and river temperature (e.g., Beschta et al., 1987; Poole and Berman, 2001; Caissie, 2006), to our knowledge, none have included all major types of impacts to provide a comprehensive context for evaluating mitigation.

Here, we quantitatively summarize and compare all human impacts to stream and river temperatures reported in a variety of existing reviews and individual studies in the scientific literature. We then synthesize 48 studies that contain thermal performance curves for stream or river organisms. We use the curves to quantify thermal sensitivity of biological processes and to compare biological sensitivity to the full range of anthropogenic impacts with stream and river temperature. We address the following questions: (i) what is the extent of available thermal performance curve data for river organisms and are there important gaps; (ii) how does biological sensitivity to temperature change vary among river taxa, biological processes, and thermal regimes; and (iii) how

do current and projected human impacts to river water temperatures compare with biological temperature sensitivity. Ultimately, we discuss how these data can help inform and guide thermal mitigation.

## METHODS

### Human Impacts

We searched the peer-reviewed scientific literature for data on human impacts to water temperature in streams and rivers. We tried to find data for as wide a range of impact types as possible, and then we calculated maximum and typical human impacts for each type. Maximum values were calculated as the largest magnitude value among the data we found for that particular impact type. Because human impacts to temperature from a given literature source were generally reported as ranges of impacts (i.e., a range from a minimum to maximum observed), typical values were calculated by taking the midrange value of each range given, and then taking the average (arithmetic mean) of all the midranges for a given impact type. For reduction of groundwater exchange, impacts ranged over several orders of magnitude, so we calculated both arithmetic and geometric means. This quantitative review is meant to be representative of the literature, but is not an exhaustive compilation. Some of the data included are from direct manipulations (e.g., loss of riparian shading), some are from studies that attribute portions of a stream heat budget to particular processes (e.g., groundwater exchange), and some are from predictive modeling (e.g., global warming). In order to characterize each type of impact separately, only data for single impacts were included; data from cumulative effects of multiple impacts were excluded except where noted.

There were some issues that were specific to certain impact types. For loss of riparian shading, we included data from partial and total loss of riparian shading that occurred together with a range of impacts to upland vegetation (from no impact to clearcut). For loss of upland vegetation, we included data only for situations where riparian vegetation remains. Impacts in winter due to loss of riparian shading or upland vegetation were not included because they can entail cooling or warming depending on time of day and other factors (Beschta et al., 1987). For global warming, we included only long-term impacts, expected to occur by mid to late century due to changes in air temperature, not changes in river flow. For reduction of groundwater exchange, we included data for reduction of catchment ground-

water input to streams and rivers and also reduction of hyporheic exchange, which is bi-directional flow between surface and groundwater along relatively short groundwater flow paths (centimeters to tens of meters). Values for reduction of groundwater exchange are for nonmeltwater dominated conditions during summer. For input of effluent discharges, we included data for discharges from both industry and municipalities.

### Biological Sensitivity

Our approach to biological sensitivity was more involved than for human impacts because the former involved calculating sensitivity from raw data rather than merely synthesizing existing data as we did for human impacts. We searched the peer-reviewed scientific literature for thermal performance curves for organism-level biological processes. Our exclusive focus on thermal performance curves eliminated many studies containing less complete descriptions of biological response to temperature (e.g., thermal tolerance limits), but the resulting dataset is clearly richer in information for understanding the biological impact of temperature changes. We focused on thermal performance curves that directly affect population dynamics of stream and river species, including survival (= 1 ) mortality) rate and reproduction (birth) rate (Begon et al., 2006). Because reproduction rate is a function of body size (Sweeney and Vannote, 1978; Beitinger and Fitzpatrick, 1979), we also searched for processes that contribute to body size, including growth rate and development rate (Begon et al., 2006). We limited our review to curves in graphical form based on acclimated organisms with constant, average, or specified percentile water temperature as the independent variable.

We searched Web of Science for citations that contained the keywords temperature or thermal; stream, river, or lotic; and a keyword associated with one of the processes of interest (growth, development, reproduction, spawn, hatch, egg, birth, death, survival, mortality). For all searches, wildcard characters and synonyms were included to retrieve citations containing variants of the keywords. We did not include the process of migration among our search terms because the importance of migration varies substantially among species and depends heavily on geographic context (e.g., climate, topography), which is not considered in this study. We included only curves for stream or river species, or stream or river populations of more cosmopolitan species. Data from both field and laboratory studies were included as they complement each other well, with field conditions being more realistic, but laboratory data more precisely

isolating the effect of temperature. Field data often had considerable scatter, so studies were included only if a trend line was drawn by the original authors. Laboratory data often had less scatter than field data, so we drew trend lines connecting laboratory data where three or more temperatures were included on the x-axis. Different findings from the same study were considered independent results and therefore included separately in our analysis if they were from separate taxa, developmental stages, ages, streams/rivers, resource levels, or seasons. Different findings from the same study were not considered independent results if they were from different portions of the same cohort (e.g., different size classes of similar age individuals from a single taxa) undergoing the same experiment, in which case a single median, average, or moderate condition was included as representative. Taxonomic resolution varied among studies, and data were included separately in our analysis at as fine a resolution as possible for a given study. We performed basic calculations to transform literature data into the forms used in our study. For example, development duration data were inverted to give development rate (Cossins and Bowler, 1987). Mortality rate data were subtracted from 1.0 to give survival rate (Begon et al., 2006). We defined reproduction as the creation of a viable new organism (i.e., an organism is born, hatches, or germinates) rather than intermediate events that may or may not lead to the creation of a new viable organism (e.g., egg production, fertilization) in keeping with our population level focus.

Organisms respond physiologically to temperature change over three time scales of increasing duration: acute response, acclimated response, and evolutionary response (Hill et al., 2004). Acute response represents immediate physiological response that occurs over seconds to hours. Here, we are concerned with acclimated response where changes in performance due to temperature change account for physiological adaptation that can occur in organisms over days to weeks. Acclimated response is most relevant for evaluating the response to many human impacts to temperature because such impacts are generally of sufficient duration for organisms to acclimate to the extent possible, and because human mitigation of such thermal impacts may be less relevant after significant evolutionary adaptation has occurred. We therefore limited our review to thermal performance curves based on acclimated organisms. Organisms were considered to be acclimated if data were from field studies, or in the case of laboratory studies, if the paper stated the organisms were acclimated, if the previous life stage was also spent at the acclimation temperature, if the majority of the organisms were present at experimental temperatures greater

than three days for invertebrates and greater than three weeks for fish (Buchanan et al., 1988; Hill et al., 2004), or if the experiments were performed on eggs.

For each thermal performance curve, we calculated $DT_{b-50}$, the temperature change required to reduce the biological process below its maximum value by 50%, and $DT_{b-10}$, the temperature change required to reduce the process by 10% of its maximum value at the steepest part of the performance curve (Figure 1). We chose DT to quantify thermal sensitivity rather than parameters already in use (e.g., $Q_{10}$) because DT allows direct comparison with changes in water temperature induced by humans. We chose 50% to represent overall sensitivity to temperature, and 10% at the steepest portion of curve to estimate curve nonlinearity. Separate values of $DT_b$ were calculated for the rising and falling portions of each curve if data were available. In calculating $DT_b$, some thermal performance curves did not explicitly show a peak temperature. In such cases, we considered the highest part on the curve that was supported by data as the peak. For curves that exhibited a sigmoidal or logistic shape, we assigned the peak to the point on the curve whose y-value was approximately 95% of the peak, to avoid counting flat portions of the curve in the resulting $DT_b$. We included only those curves where the y-axis range was large enough to calculate $DT_{b-50}$ on at least one side of the thermal optimum. Nonlinearity quantifies how much steeper the steepest part of the rising or falling curve is than the rest of the curve. We calculated nonlinearity for each rising or falling curve as the deviation of the ratio $DT_{b-50}:DT_{b-10}$ from 5.0, the value that would result for a curve that is a straight line.

This study, to our knowledge, represents the first quantitative synthesis of thermal performance curves of its kind, and the first use of DT to quantify thermal sensitivity. For this reason we intentionally kept our statistical analysis simple in order to provide a basic orientation to the dataset. We tallied the number of curves retrieved for different taxa and biological processes. We noted how completeness of the curves (presence of both rising and falling portions) varied across the dataset. Finally, we performed statistical tests on the collection of $DT_b$ values to determine whether average thermal sensitivity varied among taxonomic groups and biological processes, and to assess the overall level of curve asymmetry and nonlinearity. We divided the full set of resulting $DT_b$ values into categories in several different ways, including taxonomic groups (fish, invertebrates), biological processes (growth, development, reproduction, survival), and rising vs. falling portions of the curves (Table 1). We performed t-tests to determine whether average thermal sensitivity differed between the two

TABLE 1. Distribution of Thermal Performance
Curves Among Taxonomic Groups and Processes.

|  | Invertebrates | Fish | Total |
|---|---|---|---|
| Growth | 27 (25R/6F) | 34 (25R/26F) | 61 (50R/32F) |
| Development | 32 (32R/0F) | 10 (10R/0F) | 42 (42R/0F) |
| Reproduction | 3 (2R/3F) | 4 (2R/4F) | 7 (4R/7F) |
| Survival | 0 (0R/0F) | 10 (2R/8F) | 10 (2R/8F) |
| Total | 62 (59R/9F) | 58 (39R/38F) | 120 (98R/47F) |

Notes: Values are number of thermal performance curves in each
category. Values in parentheses give split in each category between
rising (R) and falling (F).

taxonomic groups and between rising and falling
across the entire dataset. Among the different pro-
cesses, the number of data points was sufficient to
compare growth and development for the rising parts
of the curve only. t-Tests for nonlinearity checked
whether average $DT_{b-50}:DT_{b-10}$ was significantly
different from 5.0 (using natural logarithms of $DT_{b-50}$:
$DT_{b-10}$ because the ratio itself is approximately
log-normally distributed). All t-tests performed for
this study were two-sample one-tailed t-tests run only
when n > 9 for both subsets of the data being com-
pared and only when assumptions of normality were
met (verified by visual inspection of histograms and
skew and kurtosis in the range of )2 to +2). Our
quantitative synthesis deviates from a formal meta-
analysis (Hunter and Schmidt, 1990) because our aim
is not to determine whether the effect of temperature
is real (there is already consensus in the literature
that there is a significant effect (Begon et al., 2006)),
but rather we focus on how this effect varies across
the dataset. In formal meta-analysis, results from
various studies are typically weighted by variance
(Hunter and Schmidt, 1990), but we did not weight
because variance data are too sparse among the studies
we used.

## RESULTS

### Human Impacts

We analyzed data in 28 published papers or book
chapters, many of which were summaries or compila-
tions themselves (Table 2). Although some data were
available for all seasons, the vast majority of avail-
able data were for summer. Overall, human activities
tend to increase temperatures more often than
decrease, with some notable exceptions such as bot-
tom release reservoirs in summer ($DT_h$; Figure 2,
Table 2). Each category of impact exhibits consider-
able variability in time and space due to correspond-

ing variability in both physical conditions of stream
and river systems (e.g., channel discharge, groundwa-
ter discharge and temperature, channel morphology)
and magnitude of human activity. Impacts tend to be
greater in low velocity areas within the channel than
in overall bulk mainstem flow. Table 2 focuses on
longer term effects with impacts that last years or
decades, and on base-flow (i.e., not storm) conditions,
which are present most of the time, and have higher
thermal susceptibility due to lower channel dis-
charge.

Loss of riparian shading can be caused by a wide
range of human activities, including logging, urbani-
zation, road cuts, and forest fires (Ward, 1985;
Beschta et al., 1987; Moore et al., 2005; Caissie, 2006).
Loss of riparian shading has an important thermal
effect primarily in small waterways where the canopy
can reach a significant way across the channel (Allan,
1995), and is most often reported as a warming effect
on peak or average stream temperatures in summer
(Table 2). The thermal impact of riparian shade loss
in winter can be either warming or cooling, and is
generally of smaller magnitude than summer effects
(not shown in Table 2, but see Beschta et al., 1987).
Logging and urbanization practices can entail partial
or complete loss of riparian vegetation, usually
together with loss of upland vegetation. Impacts from
loss of vegetation are generally greatest with complete
loss of both riparian and upland vegetation and least
with loss of only upland vegetation (i.e., vegetative
buffers are maintained along stream margins)
(Table 2). The effect of stream buffers varies with the
width of the buffer, the degree of thinning in the buf-
fer, and the aspect of the stream (Moore et al., 2005).

Climate change will affect stream and river tem-
peratures in many important ways, including by
altering precipitation amounts, precipitation forms,
and snow and glacier melt. However, data are avail-
able in the literature primarily for the impact of
rising air temperatures directly on water tempera-
tures (global warming in Table 2). Globally, greater
increases in minimum than maximum atmospheric
temperatures are already apparent (Karl et al., 1993;
Walther et al., 2002), and greater atmospheric warm-
ing is expected in winter than summer (Millenium-
Ecosystem-Assessment, 2005). In the United States
(U.S.), greater warming of stream water is expected
in spring than in summer or winter (Mohseni et al.,
1999). Predicted warming values from the literature
reflect this with slightly higher thermal impacts on
an annual basis than in summer (Table 2), although
this difference may not be significant. Increasing air
temperatures in urban areas due to urban heat
islands should also increase temperatures in streams,
although there is little data to isolate this effect from
other urban impacts (e.g., loss of riparian shading).

TABLE 2. Human Impacts to Stream and River Temperature ($DT_h$, °C).

| Human Impact* | Impact Type | Typical or Annual Average | | Seasonal | | | Sources |
|---|---|---|---|---|---|---|---|
| | | Typical* $DT_h$ | Max $DT_h$ | Season | Typical* $DT_h$ | Max $DT_h$ | |
| **Impacts to bulk mainstem flow** | | | | | | | |
| Loss of riparian shading | Warming | | | Summer | 4.1 | 13.0 | Reviews: (Smith, 1972; Ward, 1985; Beschta et al., 1987; Allan, 1995; Webb, 1996; Moore et al., 2005; Caissie, 2006) Individual studies: (Lynch et al., 1984; LeBlanc et al., 1997; Ebersole et al., 2003; Johnson, 2004; Rutherford et al., 2004; Dunham et al., 2007) |
| Loss of upland forest | Warming | | | Summer | 1.1 | 2.6 | Reviews: (Beschta et al., 1987; Moore et al., 2005) Individual study: (Bourque and Pomeroy, 2001) |
| Global warming | Warming | 3.2 | 8.4 | Summer | 2.8 | 7.0 | Review: (Webb, 1996) Individual studies: (Pilgrim et al., 1998; Mohseni et al., 1999; Morrison et al., 2002; Ferrari et al., 2007; Pedersen and Sand-Jensen, 2007) |
| Reduction of groundwater exchange | Warming | | | Summer | 1.1 (A) 0.2 (G) | 4.0 | Individual studies: (Story et al., 2003; Loheide and Gorelick, 2006; Burkholder et al., 2008; Hester et al., 2009) |
| Increased width-to-depth ratio | Warming | | | Summer | | 1.7 | Individual study: (LeBlanc et al., 1997) |
| Input of effluent discharges | Warming | 3.4 | 12.0 | | | | Reviews: (Smith, 1972; Webb, 1996) Individual study: (Kinouchi et al., 2007) |
| Diversion of tributary input | Warming | | | Summer | 0.7 | 1.1 | Review: (Webb, 1996) Individual studies: (Danehy et al., 2005) |
| Diversion of tributary input | Cooling | | | Summer | )0.8 | )1.0 | Individual study: (Danehy et al., 2005) |
| Large bottom-release reservoir dams | Warming | | | Winter | | 4.0 | Review: (Allan, 1995) |
| Large bottom-release reservoir dams | Cooling | | | Summer | )8.4 | )14.0 | Reviews: (Smith, 1972; Allan, 1995) |
| **Impacts to sheltered, low velocity areas of flow** | | | | | | | |
| Reduction of groundwater exchange | Warming | | | Summer | 5.6 | 12.4 | Individual studies: (Bilby, 1984; Nielsen et al., 1994; Ebersole et al., 2003; Fernald et al., 2006) |
| Diversion of tributary input | Warming | | | Summer | 5.1 | 5.3 | Reviews: (Bilby, 1984; Nielsen et al., 1994) |

*See Methods section for details of human impact categories, and how typical impacts were calculated. A, arithmetic mean; G, geometric mean.

Thermal interaction of streams and rivers with groundwater occurs both through upwelling of deeper catchment groundwater and bidirectional (hyporheic) exchange with shallower groundwater. Humans can reduce catchment groundwater input (i.e., reduce base flow) through increased surface runoff in urban areas (Leopold, 1968; Hardison et al., 2009) and reduce hyporheic exchange by channel straightening
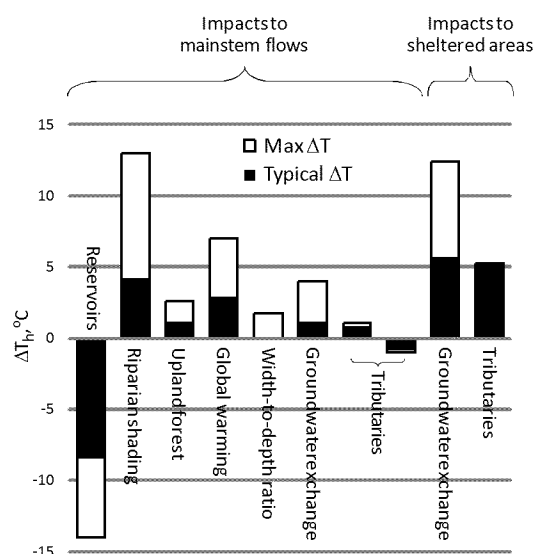
FIGURE 2. Selected Human Impacts to Stream and River Temperature During Summer ($DT_h$, $^{\circ}C$).

and simplification (Poole and Berman, 2001). Reduction of either type of interaction increases average and/or daily maximum surface water temperatures in summer, with the opposite occurring in winter (Poole and Berman, 2001; Loheide and Gorelick, 2006; Arrigoni et al., 2008) in nonmeltwater dominated conditions. The opposite occurs in alpine or arctic systems during periods when glacial- or snow-melt dominates (Brown et al., 2007), or from increases in base flow. The thermal effect of reduced catchment groundwater input has rarely been directly quantified (but see LeBlanc et al., 1997), but can be estimated by studies that quantify the effect of groundwater on stream heat budgets (Table 2). Changes in channel morphology can impact hyporheic exchange, but also impact atmospheric heat exchange, for example by increasing channel width-to-depth ratio (Table 2; LeBlanc et al., 1997).

The increased thermal mass of water behind reservoir dams generally damps annual temperature cycles in downstream reaches relative to free flowing conditions (Ward, 1985; Webb, 1996; Caissie, 2006). In addition, thermal stratification and water releases below the thermocline in summer often lead to greater summer cooling than winter warming (Table 2). Tributary input has mostly been reported as a cooling influence on bulk stream temperatures or more isolated patches during summer (Bilby, 1984; Nielsen et al., 1994; Webb, 1996). Consequently, human diversion of tributary input would often have a warming effect (Table 2). Nevertheless, some tributaries should have a warming influence on streams, and diversion of these tributaries would have a cooling effect (Danehy et al., 2005). Effluent discharges from municipal sewage treatment plants, power plants, and other industry also typically warm the receiving water (Webb, 1996) (Table 2).

## Biological Sensitivity

We analyzed 120 thermal performance curves from 48 published papers or book chapters (Appendix, Table 1). Curves that met our criteria were available for fish and invertebrates, but not for microbes or macrophytes. Most curves were for growth or development, with less for reproduction or survival (Table 1). All thermal performance curves for fish (n = 58) were for individual species, and included 21 species from 14 genera and 9 families, although the majority were for salmonids (Table 3). The taxonomic resolution of the invertebrate data (n = 62) was typically species or genus, although it was occasionally as coarse as the family level. Most curves for invertebrates were for insects (n = 40), with the remainder for crustaceans (n = 22) (Table 4). The majority of the data were from temperate organisms (n = 110) with only a few tropical (n = 10). Most data were from laboratory experiments, with <20% from field studies, although a significant number of semi-controlled field experiments blurred this distinction.

TABLE 3. Distribution of Thermal Performance Curves Among Fish Taxonomic Groups.

| Taxonomic Group | Representative Organisms | Number of Curves |
|---|---|---|
| Acipenseridae | Sturgeons | 2 |
| Clupeidae | Herrings, shads | 2 |
| Cottidae | Sculpins | 5 |
| Cyprinidae | Carps, minnows | 7 |
| Esocidae | Pikes, pickerels | 2 |
| Moronidae | Basses | 4 |
| Percichthyidae | Southern hemisphere perches | 1 |
| Percidae | Perches, walleyes | 1 |
| Salmonidae | Salmon, trout, char | 34 |

TABLE 4. Distribution of Thermal Performance Curves Among Invertebrate Taxonomic Groups.

| Taxonomic Group | Representative Organisms | Number of Curves |
|---|---|---|
| Insects | | |
| Diptera | True flies | 19 |
| Ephemeroptera | Mayflies | 15 |
| Plecoptera | Stoneflies | 3 |
| Trichoptera | Caddisflies | 3 |
| Crustaceans | | |
| Amphipoda | Amphipods | 10 |
| Cladocera | Water fleas | 8 |
| Copepoda | Copepods | 1 |
| Decapoda | Crayfish, crabs | 3 |

FIGURE 3. (a) Average Temperature Change Required to Reduce Organism-Level Biological Process Rate Below Maximum by 50% ($DT_{b-50}$), Segregated by Taxa (includes all processes) (bar heights indicate means, error bars represent ± standard error); (b) Average Temperature Change Required to Reduce Organism-Level Biological Process Rate Below Maximum by 50% ($DT_{b-50}$), Segregated by Taxa and Process (includes only data for rising curves where n > 9) (bar heights indicate means, error bars represent ± standard error).

$DT_{b-50}$ averaged 7.4ᴺC (n = 145) and $DT_{b-10}$ averaged 1.0ᴺC (n = 143) across the entire dataset (small values of $DT_b$ indicate high sensitivity to temperature change, and large values indicate low sensitivity). Fish were on average more sensitive than invertebrates to temperature change when compared across the entire dataset (all processes, both rising and falling, p < 0.001; Figure 3a). This trend also held for just growth and development individually (among only rising curves for growth and development, p < 0.001; Figure 3b). Average thermal sensitivity appeared to vary among processes as well, but sample size was generally insufficient for statistical comparison (Figure 4, Table 1). Development was slightly more sensitive to temperature than growth (among only rising curves, Figure 3b) but this difference was not significant for invertebrates (p = 0.43) and only marginally significant for fish (p = 0.083). Thermal sensitivity therefore appeared to vary more with taxa than process.
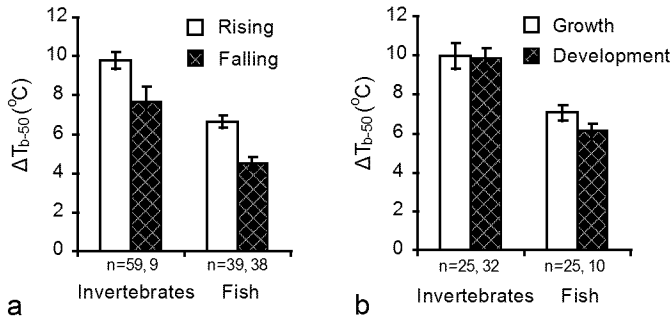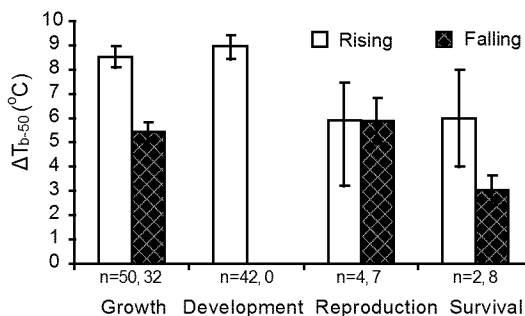


FIGURE 4. Average Temperature Change Required to Reduce Organism-Level Biological Process Rate Below Maximum by 50% ($DT_{b-50}$), Segregated By Process (includes all taxa). Bar heights indicate means, error bars represent ± standard error, except where n < 5 where error bars represent range.

Across the entire dataset, organism processes were more sensitive to temperature change on the falling curves, that is, at temperatures above the optimum, than the rising curves (p < 0.001), indicating an asymmetry to many thermal performance curves. This asymmetry appeared to maintain itself across individual taxa and processes (Figures 3 and 4), but sample sizes were sufficient to confirm this only for fish and growth (p < 0.001). The thermal performance curves were on average nonlinear (p < 0.001 for rising and falling), with falling curves on average more nonlinear than rising curves (back-transformed average $DT_{b-50}:DT_{b-10}$ ratios of 9.7 and 6.9, respectively). Nonlinearity was maintained across taxa and processes (back-transformed average rising/falling ratios of 7.0/8.6 for invertebrates, 7.0/10.3 for fish, 7.9/11.0 for growth, 6.1/NA for development, 11.1/9.7 for reproduction, and 8.7/8.8 for survival; NA = not applicable), but sample size was large enough and the log-transformed values distributed sufficiently normally to verify this only for fish (p < 0.001 for rising and falling), invertebrates for rising curves (p < 0.001), and growth (p < 0.001 for rising and falling). Because the papers summarized in our study commonly used linear regression to analyze thermal data, our quantification of nonlinearity is likely an underestimate.

## DISCUSSION

Most typical human impacts alter stream or river temperatures by about 5ᴺC or less (Figure 2). However, the overall magnitude varies considerably: during summer, reservoir dams have the greatest potential for cooling, and loss of riparian shading has the greatest potential for warming, with both impacts capable of altering temperatures by more than 10ᴺC. Human impacts also vary in spatial and temporal scope. Some human activities can result in significant thermal impacts for many kilometers due to either a large temperature change imparted at a specific point (e.g., reservoirs) or a more modest temperature change imparted over a large length of waterway (e.g., extensive loss of riparian shading) (Rounds, 2007). Nevertheless, most types of individual actions are more modest in degree and spatial extent (e.g., localized cutting of riparian vegetation), causing comparatively localized impacts (Story et al., 2003; Johnson, 2004). Furthermore, some impacts occur in sheltered or low velocity areas, and their effects do not even extend across the full height or width of the river (Fernald et al., 2006). Nevertheless, such sheltered areas may represent critical habitat for a

variety of organisms, including life stages of organisms that at other times migrate elsewhere in the landscape, such that local impacts may be quite important to the overall ecology of a river system. Furthermore, most types of short-term or local impacts are quite common, and can accumulate through time and space to create long-term, widespread impacts. Global warming impacts may take decades to materialize and span the planet, although they also exhibit geographic variability.

The magnitudes of several anthropogenic thermal impacts ($DT_h$) approach or exceed the average $DT_{b-50}$, and nearly all exceed the average $DT_{b-10}$, confirming substantial potential to impact organisms (Appendix, Figures 2 and 3). Among taxa, our results suggest that human impacts may affect fish more than invertebrates (Figure 3a). However, our data are representative of the literature from which they are drawn, and are not necessarily representative of the full range of taxa on the landscape. More thermal performance data would therefore be beneficial in areas where the dataset was relatively weak (e.g., low altitude/latitude fish, noninsect invertebrates, coolwater invertebrates, and field studies in general). In particular, given the dominance of salmonids in the fish dataset, we conducted a t-test comparison of all $DT_{b-50}$ data between fish in the family Salmonidae on the one hand and those in all other fish families combined on the other, and found means to not be statistically different ($p = 0.21$). Furthermore, our practice of eliminating curves where the y-axis range was too small to calculate $DT_{b-50}$ may bias the results somewhat toward more sensitive taxa and accordingly underestimate average $DT_{b-50}$.

The net impact of a given temperature change on an individual organism is a complex function of thermal impacts on multiple organism-level processes, each of which can be affected by temperature duration and variability (Hokanson et al., 1977; Cossins and Bowler, 1987). Direct response of organism function to temperature change (i.e., the shape of the thermal performance curve) can also be affected by other aspects of the local environment such as existing levels of food availability and competition (Brett, 1979; Hill and Magnuson, 1990; Hughes and Grand, 2000). Furthermore, temperature changes can have indirect effects on organisms by affecting the abundance of food resources, competitors, and predators. A thorough understanding of organism response to temperature change therefore requires complex bioenergetic modeling of multiple life stages at multiple locations interacting with other species and other aspects of their environment. Nevertheless, thermal performance curves, which define several important traits including optimum growth temperature and thermal tolerance limits, can help anticipate thermal impacts to various species by helping quantify thermal habitat, an important dimension of overall habitat. Habitat offering optimal growth temperatures is expected to impart size advantages that will increase survival in the face of predators and other types of mortality (Billman et al., 2006). Defining thermal tolerance limits is also important to characterizing habitat and to understanding impacts at the species level (Hokanson et al., 1977; Carveth et al., 2007). We located more than 100 thermal performance curves for a wide variety of stream and river organisms (e.g., 21 fish species), including a large number of species of considerable interest to resource managers such as various species of salmon as well as macroinvertebrates in the EPT (Ephemeroptera, Plecoptera, and Trichoptera) orders that are often used as indicator organisms (USEPA, 1999; Lackey et al., 2006). This study provides a lengthy compendium of sources of thermal performance information for these and other taxa (Appendix).

Although the thermal performance curves analyzed in our study exhibited significant asymmetry, there was little discussion of this asymmetry among the papers from which the curves were drawn. Such asymmetry appears to be seldom discussed in the scientific literature, but has been occasionally acknowledged in general terms (Alexandrov, 1977; Huey and Kingsolver, 1989) and specifically for plant growth (Sutcliffe, 1977; Fitter and Hay, 2002). The humped shape of thermal performance curves, together with their asymmetry and nonlinearity, means that organism response to temperature change depends on where the existing thermal regime falls on the curve. In particular, the impact of temperature change on an organism depends on whether the occupied habitat is thermally optimal, or warmer or cooler instead. For organisms already occupying optimal habitat, the human tendency to increase water temperature is of particular concern, because growth is often more sensitive at temperatures above (falling curve) than below (rising curve) the optimum (Figure 3a). For example, growth and survival in many coldwater and some warmwater fishes are expected to decline as temperatures rise with global warming and other human impacts (Bear et al., 2007). In contrast, for organisms that operate below the optimum, warming impacts would occur on the rising curve, possibly providing a functional benefit (Leach and Houde, 1999; Whitledge and Rabeni, 2002; Billman et al., 2006). The relationship of occupied habitat to thermal optima varies with context. For example, organisms at the low latitude/altitude end of their range may occupy habitat that is warmer relative to the thermal optimum than those at the high latitude/altitude end of their range. Such low latitude/altitude organisms may be impacted by warming differently than organisms elsewhere in their range, although this

depends on whether thermal optima are locally adapted, a point that is still debated in the literature (Wagner and Wahl, 2007). Optimum temperatures are also affected by other factors such as organism age, food intake, and time of year (Nichelmann, 1983; Cossins and Bowler, 1987).

Understanding organism response to temperature change and thermal suitability of habitat also requires accounting for behavioral thermoregulation, where organisms move through their environment to seek out preferred temperatures. Although thermal heterogeneity is not as ubiquitous in streams and rivers as it is in lakes due to the preponderance of turbulent flow (Giller and Malmqvist, 1998), heterogeneity nonetheless exists in certain situations, particularly in slower moving regions such as backwater areas, pool bottoms, and macrophyte beds, or at locations of concentrated water inflow such as tributary mouths and areas of groundwater or hyporheic upwelling (Bilby, 1984; Clark et al., 1999; Torgersen et al., 1999). Behavioral thermoregulation has accordingly been observed among certain river species, particularly among more mobile species such as fish (Ebersole et al., 2001; Goniea et al., 2006). Nevertheless, if anthropogenic temperature changes are large enough, there is potential to shift the entire stream temperature profile sufficiently to exceed the compensatory ability of behavioral thermoregulation. Furthermore, many factors influence aquatic organism movement and habitat selection in addition to temperature including light, dissolved oxygen, prey density, competitors, and predators (Giller and Malmqvist, 1998; Wagner and Wahl, 2007).

Although the biological effects of temperature change will vary among taxa and setting, human actions to reduce thermal impacts to aquatic species are clearly needed. Thermal mitigation in streams and rivers is not extensively discussed in scientific journals, and then mainly in relation to mitigating cold water hypolimnetic releases from reservoirs (e.g., Sherman et al., 2007) and stream warming due to riparian logging (e.g., Broadmeadow and Nisbet, 2004). Additional coverage exists in reports associated with the Willamette River temperature TMDL in Oregon (Hulse et al., 2007; Rounds, 2007). Specific mitigation strategies have included riparian shade restoration, selective depth withdrawal towers for reservoirs, and reduction of municipal water discharge volumes, all within the context of a temperature trading program. Developing and testing mitigation strategies, and evaluating their impact on target organisms and ecosystems, nevertheless remains a critical research need. The nature of some human thermal impacts to streams and rivers will require local actions (e.g., riparian re-vegetation), but others will require greater regional coordination

(e.g., scheduling of water releases from reservoirs to coincide with peak summer temperatures in rivers). Finally, global impacts like climate change must be addressed on an international basis, although local mitigation of other thermal impacts may help compensate for climate change.

## CONCLUSIONS

Human activities such as land-use change and water resources management increasingly impact stream and river temperatures by modifying river flow, riparian shading, channel form, and climate. Such thermal impacts in turn can have significant, often negative, impacts on aquatic organisms. Efforts at thermal mitigation are just beginning but are expected to grow substantially in future decades. Yet understanding the biological consequences of human thermal impacts, as well as mitigation options, is challenging. This study provides context for management in two ways. First, we summarize the full spectrum of human thermal impacts to help inform thermal management by quantifying the relative magnitudes of all mitigation options. Our results confirm the wide range of thermal impact magnitudes that range in some cases to more than $10^{\circ}$C for reservoirs and riparian shading. Impacts are consistently greater in sheltered areas away from mainstem flow, where groundwater exchange can also impact temperatures by more than $10^{\circ}$C. Second, we synthesize biological sensitivity to temperature shifts. Our synthesis supplements the popular thermal threshold approach by quantifying impact to biological processes to thermal shifts via thermal performance curves, which relate organism-level processes to temperature. Our results confirm the sensitivity of stream and river organisms to temperature change: many human impacts are sufficient to alter biological processes by 50% or more. Fish appear more sensitive to temperature change than invertebrates, at least among the available data. In addition, thermal performance curves appear to be consistently asymmetric and nonlinear such that thermal sensitivity varies depending on the temperature range considered. In particular, organisms are often most sensitive to warming above their thermal optima. Our synthesis provides a compendium of 120 thermal performance curves (Appendix) where such information can be located and cross-referenced to the original sources. Nevertheless, our literature search also revealed that certain taxa form a disproportionate share of existing data (e.g., salmonids), indicating the value of further thermal sensitivity research.

# APPENDIX

Detailed thermal performance curve data.

| Taxa | Taxonomic Group | LifeStage (If Given) | Process | $DT_{e\text{-}50}$, Rising | $DT_{e\text{-}50}$, Falling | $DT_{e\text{-}10}$, Rising | $DT_{e\text{-}10}$, Falling | Unit | Source |
|---|---|---|---|---|---|---|---|---|---|
| **Fish** | | | | | | | | | |
| Acipenser medirostris | Acipenseridae | Egg | Development | 7.2 | | 1.18 | | 1/h | Van Eenennaam et al. (2005) |
| Acipenser medirostris | Acipenseridae | Egg | Reproduction | | 8 | | 0.6 | % | Van Eenennaam et al. (2005) |
| Alosa sapidissima | Clupeidae | Larva | Survival | 8 | | 0.7 | | % | Leach and Houde (1999) |
| Alosa sapidissima | Clupeidae | Larva | Growth | 9 | | 1.6 | | % | Leach and Houde (1999) |
| Chondrostoma nasus | Cyprinidae | Embryo | Growth | 4 | | 0.8 | | %/day | Schiemer et al. (2003) |
| Chondrostoma nasus | Cyprinidae | Larva | Growth | 7 | | 1.4 | | %/day | Schiemer et al. (2003) |
| Cottus gobio | Cottidae | Adult - 2 years | Growth | | 1.5 | | 0.3 | 1/year | Abdoli et al. (2007) |
| Cottus gobio | Cottidae | Adult - 3 years | Growth | | 1.6 | | 0.32 | 1/year | Abdoli et al. (2007) |
| Cottus gobio | Cottidae | Adult - 4 years | Growth | | 1.7 | | 0.34 | 1/year | Abdoli et al. (2007) |
| Cottus gobio | Cottidae | Adult - 5 years | Growth | | 1.8 | | 0.36 | 1/year | Abdoli et al. (2007) |
| Cottus kazika | Cottidae | | Growth | 10 | 6.5 | 1.4 | 0.5 | % | Takeshita et al. (2005) |
| Esox lucius | Esocidae | Egg | Development | 6.6 | | 1.08 | | 1/day | Farrell et al. (2006) |
| Esox lucius | Esocidae | Larva | Development | 4.3 | | 0.74 | | 1/day | Farrell et al. (2006) |
| Iotichthus phlegethontis | Cyprinidae | | Growth | 7 | | 0.56 | | mg/day | Billman et al. (2006) |
| Maccullochella peelii peelii | Percichthyidae | Egg and juvenile | Survival | 4 | | 0.6 | | % | Todd et al. (2005) |
| Meda fulgida | Cyprinidae | Adult | Survival | | 2.1 | | 0.2 | % | Carveth et al. (2007) |
| Meda fulgida | Cyprinidae | Adult | Growth | | 6 | | 1.2 | mm/day | Carveth et al. (2007) |
| Morone saxatilis | Moronidae | Young of year | Growth | 2.7 | | 0.54 | | %/day | Hurst and Conover (1998) |
| Morone saxatilis | Moronidae | Larva | Growth | 6.2 | | 1.24 | | mg/day | Secor and Houde (1995) |
| Morone saxatilis | Moronidae | Larva | Survival | | 5 | | 0.36 | %/day | Secor and Houde (1995) |
| Morone saxatilis | Moronidae | Egg | Survival | | 4.2 | | 0.38 | %/day | Secor and Houde (1995) |
| Notropis topeka – with tapeworms | Cyprinidae | | Growth | 5.1 | 4 | 0.7 | 0.18 | %/day | Koehle and Adelman (2007) |
| Notropis topeka – without tapeworms | Cyprinidae | | Growth | 6.9 | 5.4 | 0.92 | 0.34 | %/day | Koehle and Adelman (2007) |
| Oncorhynchus clarki utah | Salmonidae | Adult | Survival | | 1.2 | | 0.2 | % | Johnstone and Rahel (2003) |
| Oncorhynchus clarkii lewisi | Salmonidae | Juvenile | Survival | | 3 | | 0.35 | % | Bear et al. (2007) |
| Oncorhynchus clarkii lewisi | Salmonidae | Juvenile | Growth | 5.9 | 5.8 | 0.4 | 0.4 | % | Bear et al. (2007) |
| Oncorhynchus mykiss | Salmonidae | Juvenile | Survival | | 2.3 | | 0.28 | % | Bear et al. (2007) |
| Oncorhynchus mykiss | Salmonidae | Juvenile | Growth | | 8 | | 1 | % | Bear et al. (2007) |
| Oncorhynchus mykiss | Salmonidae | Embryo | Development | 6.8 | | 1.18 | | 1/day | Brannon et al. (2004) |
| Oncorhynchus mykiss | Salmonidae | Juvenile | Growth | | 3.7 | | 0.74 | % | Magoulick and Wilzbach (1998) |
| Oncorhynchus nerka | Salmonidae | Egg | Reproduction | | 2.65 | | 0.53 | % | Hendry et al. (1998) |
| Oncorhynchus tshawytscha | Salmonidae | Smolt | Survival | | 5.5 | | 0.54 | % | Baker et al. (1995) |

Appendix Continued

| Taxa | Taxonomic Group | LifeStage (If Given) | Process | $DT_{e-50}$, Rising | $DT_{e-50}$, Falling | $DT_{e-10}$, Rising | $DT_{e-10}$, Falling | Unit | Source |
|---|---|---|---|---|---|---|---|---|---|
| Oncorhynchus tshawytscha | Salmonidae | Egg | Development | 7.7 | | 1.34 | | 1/day | Crisp (1981) |
| Oncorhynchus tshawytscha | Salmonidae | | Survival | | 0.92 | | 0.184 | % | Crozier and Zabel (2006) |
| Oncorhynchus tshawytscha 3.0% ration | Salmonidae | | Growth | 7 | 5 | 1.14 | 0.54 | %/day | Brannon et al. (2004) |
| Oncorhynchus tshawytscha 5.0% ration | Salmonidae | | Growth | 8.7 | 4.4 | 1.24 | 0.32 | %/day | Brannon et al. (2004) |
| Oncorhynchus tshawytscha 7.5% ration | Salmonidae | | Growth | 10.2 | 5 | 1.58 | 0.34 | %/day | Brannon et al. (2004) |
| Oncorhynchus tshawytscha max ration | Salmonidae | | Growth | 11.3 | 5.3 | 1.66 | 0.14 | %/day | Brannon et al. (2004) |
| Oncorhynchus tshawytscha min ration | Salmonidae | | Growth | 5 | 5 | 0.84 | 0.6 | %/day | Brannon et al. (2004) |
| Salmo gairdneri | Salmonidae | Egg | Development | 5.8 | | 0.94 | | 1/day | Crisp (1981) |
| Salmo gairdneri | Salmonidae | Juvenile | Growth | 8.7 | | 1.66 | | %/day | Hokanson et al. (1977) |
| Salmo salar | Salmonidae | Juvenile | Growth | 5.7 | | 0.5 | | % | Bacon et al. (2005) |
| Salmo salar | Salmonidae | Egg | Development | 5.3 | | 0.86 | | 1/day | Crisp (1981) |
| Salmo salar | Salmonidae | Parr | Growth | 5.5 | 3.5 | 1.1 | 0.7 | % | Elliott and Hurley (1997) |
| Salmo salar – river alta | Salmonidae | Parr | Growth | 8 | 4 | 1.2 | 0.2 | % | Jonsson et al. (2001) |
| Salmo salar – river imsa | Salmonidae | Parr | Growth | 8 | 5 | 1 | 0.3 | % | Jonsson et al. (2001) |
| Salmo salar – river lone | Salmonidae | Parr | Growth | 7 | 5 | 0.8 | 0.3 | % | Jonsson et al. (2001) |
| Salmo salar – river stryn | Salmonidae | Parr | Growth | 7 | 5 | 1 | 0.3 | % | Jonsson et al. (2001) |
| Salmo salar – river suidai | Salmonidae | Parr | Growth | 7 | 6 | 1 | 0.5 | % | Jonsson et al. (2001) |
| Salmo trutta | Salmonidae | Egg | Development | 4.2 | | 0.62 | | 1/day | Crisp (1981) |
| Salmo trutta | Salmonidae | Juvenile | Growth | 8 | 6.5 | 1.2 | 0.4 | % | Ojanguren et al. (2001) |
| Salmo trutta | Salmonidae | Egg (fertilization to H50) | Reproduction | 3.2 | 6 | 0.3 | 0.44 | % | Vernier (1969) |
| Salmo trutta | Salmonidae | Egg (H50 to Stage 37) | Reproduction | 7 | 4.2 | 0.9 | 0.5 | % | Vernier (1969) |
| Salvelinus confluentus | Salmonidae | Adult | Growth | 5.7 | 5.7 | 0.6 | 0.6 | g/day | Selong et al. (2001) |
| Salvelinus confluentus – with Salvelinus fontinalis | Salmonidae | Age 0 | Growth | | 6.8 | | 0.56 | g/day | McMahon et al. (2007) |
| Salvelinus confluentus – without Salvelinus fontinalis | Salmonidae | Age 0 | Growth | | 7.2 | | 0.76 | g/day | McMahon et al. (2007) |
| Salvelinus fontinalis | Salmonidae | Egg | Development | 5.6 | | 0.94 | | 1/day | Crisp (1981) |
| Sander lucioperca | Percidae | Egg | Development | 7.6 | | 1.26 | | 1/h | Lappalainen et al. (2003) |
| **Invertebrates** | | | | | | | | | |
| Acroperus harpae | Cladocera | Egg | Development | 7.7 | | 1.32 | | 1/day | Bottrell (1975) |
| Afronurus | Ephemeroptera | | Growth | 12 | | 2.4 | | %/day | Salas and Dudgeon (2001) |
| Alona affinis | Cladocera | Egg | Development | 9 | | 1.6 | | 1/day | Bottrell (1975) |
| Ameletus | Ephemeroptera | | Growth | 11.1 | | 1.42 | | %/day | Pritchard and Zloty (1994) |
| Apatania fimbriata | Trichoptera | | Development | 11.2 | | 1.98 | | 1/day | Enders and Wagner (1996) |
| Australopelopia prionoptera – temperate | Diptera | Pupa | Development | 12.5 | | 1.52 | | 1/day | McKie et al. (2004) |
| Australopelopia prionoptera – temperate | Diptera | Larva | Development | 13.5 | | 2.2 | | 1/day | McKie et al. (2004) |
| Australopelopia prionoptera – tropical | Diptera | Pupa | Development | 14.5 | | 1.8 | | 1/day | McKie et al. (2004) |
| Australopelopia prionoptera – tropical | Diptera | Larva | Development | 12.5 | | 1.46 | | 1/day | McKie et al. (2004) |
| Baetidae | Ephemeroptera | | Growth | 14 | | 2.8 | | %/day | Salas and Dudgeon (2001) |
| Baetis | Ephemeroptera | | Growth | 14 | | 2.8 | | g/day | Benke et al. (1992) |
| Baetis alpinus | Ephemeroptera | Egg | Development | 4.2 | | 0.79 | | 1/day | Knispel et al. (2006) |
| Cheumatopsyche brevilineata | Trichoptera | Larva | Growth | 12 | | 2.4 | | % | Mochizuki et al. (2006) |
| Cheumatopsyche brevilineata | Trichoptera | Larva | Development | 9 | | 1.8 | | 1/development period | Mochizuki et al. (2006) |

Appendix  Continued

| Taxa | Taxonomic Group | LifeStage (If Given) | Process | $DT_{e-50}$, Rising | $DT_{e-50}$, Falling | $DT_{e-10}$, Rising | $DT_{e-10}$, Falling | Unit | Source |
|---|---|---|---|---|---|---|---|---|---|
| Chironomini (Chironomidae) | Diptera | | Growth | 12 | | 0.86 | | %/day | Hauer and Benke (1991) |
| Chironomini (subset of Chironominae) | Diptera | Larva | Growth | 10.5 | | 0.86 | | %/day | Reynolds and Benke (2005) |
| Choroterpes | Ephemeroptera | | Growth | 5 | | 1 | | %/day | Salas and Dudgeon (2001) |
| Chydorus sphaericus | Cladocera | Egg | Development | 8.9 | | 1.56 | | 1/day | Bottrell (1975) |
| Cinygmina | Ephemeroptera | | Growth | 14 | | 2.8 | | %/day | Salas and Dudgeon (2001) |
| Deleatidium (Leptophlebiidae) – stony creek | Ephemeroptera | | Growth | 6 | | 0.56 | | %/day | Huryn (1996) |
| Deleatidium (Leptophlebiidae) – sutton stream | Ephemeroptera | | Growth | 6.6 | | 0.68 | | %/day | Huryn (1996) |
| Dinocras (Perlidae) | Plecoptera | Egg | Reproduction | 6 | 10 | 0.5 | 0.5 | % | Zwick (1996) |
| Dinocras cephalotes (Perlidae) | Plecoptera | | Development | 12 | | 2.4 | | 1/day | Frutiger (1996) |
| Ecdyonurus picteti | Ephemeroptera | Egg | Development | 4 | | 0.8 | | 1/day | Knispel et al. (2006) |
| Echinocladius martini | Diptera | Pupa | Development | 10.8 | | 1.95 | | 1/day | McKie and Pearson (2006) |
| Echinocladius martini – temperate | Diptera | Pupa | Development | 13 | | 1.28 | | 1/day | McKie et al. (2004) |
| Echinocladius martini – tropical | Diptera | Pupa | Development | 14 | | 2.8 | | 1/day | McKie et al. (2004) |
| Echinocladius martini – tropical | Diptera | Larva | Development | 12 | | 1.6 | | 1/day | McKie et al. (2004) |
| Eucyclops agilis | Copepoda | Egg | Development | 8 | | 1.4 | | 1/day | Bottrell (1975) |
| Eurycercus lamellatus | Cladocera | Egg | Development | 7.5 | | 1.35 | | 1/day | Bottrell (1975) |
| Gammarus fossarum | Amphipoda | Juvenile | Development | 8.5 | | 1.7 | | 1/day | Pockl (1992) |
| Gammarus fossarum | Amphipoda | Newborn | Growth | 9.5 | | 1.7 | | %/day | Pockl (1992) |
| Gammarus fossarum | Amphipoda | Juvenile | Growth | 7 | | 1.5 | | %/day | Pockl (1992) |
| Gammarus fossarum | Amphipoda | Adult | Growth | 12 | | 2.5 | | %/day | Pockl (1992) |
| Gammarus pulex | Amphipoda | Newborn | Growth | 13 | | 1 | | %/day | Sutcliffe et al. (1981) |
| Gammarus pulex | Amphipoda | | Growth | 9 | 11 | 0.4 | | %/day | Sutcliffe et al. (1981) |
| Gammarus roeseli | Amphipoda | Juvenile | Development | 7.8 | | 1.56 | | 1/day | Pockl (1992) |
| Gammarus roeseli | Amphipoda | Newborn | Growth | 8.5 | | 1.3 | | %/day | Pockl (1992) |
| Gammarus roeseli | Amphipoda | Juvenile | Growth | 8 | | 1.2 | | %/day | Pockl (1992) |
| Gammarus roeseli | Amphipoda | Adult | Growth | 11 | | 2.5 | | %/day | Pockl (1992) |
| Graptoleberis testudinaria | Cladocera | Egg | Development | 7.3 | | 1.38 | | 1/day | Bottrell (1975) |
| Nanocladius | Diptera | Pupa | Development | 13 | | 2.04 | | 1/day | McKie et al. (2004) |
| Orconectes eupunctus | Decapoda | Adult | Growth | | 8 | | 1.6 | %/day | Whitledge and Rabeni (2002) |
| Orconectes punctimanus | Decapoda | Adult | Growth | 4 | | 0.8 | | %/day | Whitledge and Rabeni (2002) |
| Orconectes virilis | Decapoda | Adult | Growth | | 4 | | 0.8 | %/day | Whitledge and Rabeni (2002) |
| Orthocladiinae (subset of Chironomidae) | Diptera | Larva | Growth | 8 | 9 | 0.5 | 1 | %/day | Reynolds and Benke (2005) |
| Parameletus chelifer | Ephemeroptera | Nymph | Growth | 16.86 | | 1.1025 | | mm/day | Soderstrom (1988) |
| Paramerina | Diptera | Pupa | Development | 6.9 | | 1.38 | | 1/day | McKie et al. (2004) |
| Paramerina | Diptera | Larva | Development | 18 | | 1.36 | | 1/day | McKie et al. (2004) |
| Perla grandis + Perlis marginata (Perlidae) | Plecoptera | | Development | 9 | | 1.8 | | 1/day | Frutiger (1996) |
| Pleuroxus uncinatus | Cladocera | Egg | Development | 7.5 | | 1.4 | | 1/day | Bottrell (1975) |
| Polypedilum australotropicus | Diptera | Pupa | Development | 10 | | 2.2 | | 1/day | McKie and Pearson (2006) |
| Polypedilum australotropicus | Diptera | Pupa | Development | 10 | | 1.46 | | 1/day | McKie et al. (2004) |
| Polypedilum australotropicus | Diptera | Larva | Development | 12.6 | | 1.78 | | 1/day | McKie et al. (2004) |
| Rhithrogena loyolaea | Ephemeroptera | Egg | Reproduction | | 4.8 | | 0.9 | % | Humpesch and Elliott (1980) |
| Rhithrogena semicolorata | Ephemeroptera | Egg | Reproduction | 7.5 | 5.5 | 0.5 | | % | Humpesch and Elliott (1980) |
| Rhithrogena semicolorata | Ephemeroptera | Egg | Development | 6 | | 0.98 | | 1/day | Humpesch and Elliott (1980) |
| Sida crystallina | Cladocera | Egg | Development | 6.5 | | 1.14 | | 1/day | Bottrell (1975) |
| Simocephalus vetulus | Cladocera | Egg | Development | 7.3 | | 1.3 | | 1/day | Bottrell (1975) |
| Stenonema (now Maccaffertium) | Ephemeroptera | | Growth | 7 | | 1 | | g/day | Benke et al. (1992) |
| Tanytarsini (Chironomidae) | Diptera | | Growth | 10 | 9 | 0.8 | 1 | %/day | Hauer and Benke (1991) |
| Tanytarsini (subset of Chironominae) | Diptera | Larva | Growth | 8.4 | 7.6 | 0.68 | 0.8 | %/day | Reynolds and Benke (2005) |

LITERATURE CITED

Abdoli, A., D. Pont, and P. Sagnes, 2007. Intrabasin Variations in Age and Growth of Bullhead: The Effects of Temperature. Journal of Fish Biology 70:1224-1238.

Alexandrov, Y.Y., 1977. Cells, Molecules and Temperature: Conformational Flexibility of Macromolecules and Ecological Adaptation. Spring-Verlag, Berlin.

Allan, J.D., 1995. Stream Ecology: Structure and Function of Running Waters. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Arrigoni, A.S., G.C. Poole, L.A.K. Mertes, S.J. O'Daniel, W.W. Woessner, and S.A. Thomas, 2008. Buffered, Lagged, or Cooled? Disentangling Hyporheic Influences on Temperature Cycles in Stream Channels. Water Resources Research 44:W09418.

Bacon, P.J., W.S.C. Gurney, W. Jones, I.S. McLaren, and A.F. Youngson, 2005. Seasonal Growth Patterns of Wild Juvenile Fish: Partitioning Variation Among Explanatory Variables, Based on Individual Growth Trajectories of Atlantic Salmon (Salmo Salar) Parr. Journal of Animal Ecology 74:1-11.

Baker, P.F., T.P. Speed, and F.K. Ligon, 1995. Estimating the Influence of Temperature on the Survival of Chinook Salmon Smolts (Oncorhynchus-Tshawytscha) Migrating Through the Sacramento-San-Joaquin River Delta of California. Canadian Journal of Fisheries and Aquatic Sciences 52:855-863.

Bear, E.A., T.E. McMahon, and A.V. Zale, 2007. Comparative Thermal Requirements of Westslope Cutthroat Trout and Rainbow Trout: Implications for Species Interactions and Development of Thermal Protection Standards. Transactions of the American Fisheries Society 136:1113-1121.

Begon, M., C.R. Townsend, and J.L. Harper, 2006. Ecology (Fourth Edition). Blackwell Publishing, Malden, Massachusetts.

Beitinger, T.L. and L.C. Fitzpatrick, 1979. Physiological and Ecological Correlates of Preferred Temperature in Fish. American Zoologist 19:319-329.

BenDor, T., J. Sholtes, and M.W. Doyle, 2009. Landscape Characteristics of a Stream and Wetland Mitigation Banking Program. Ecological Applications 19:2078-2092.

Benke, A.C., F.R. Hauer, D.L. Stites, J.L. Meyer, and R.T. Edwards, 1992. Growth of Snag-Dwelling Mayflies in a Blackwater River – the Influence of Temperature and Food. Archiv Fur Hydrobiologie 125:63-81.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra, 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions. In: Streamside Management: Forestry and Fishery Interactions, E.O. Salo and T.W. Cundy (Editors). University of Washington, Seattle, Washington, pp. 191-232.

Bilby, R.E., 1984. Characteristics and Frequency of Cool-Water Areas in a Western Washington Stream. Journal of Freshwater Ecology 2:593-602.

Billman, E.J., E.J. Wagner, and R.E. Arndt, 2006. Effects of Temperature on the Survival and Growth of Age-0 Least Chub (Iotichthys Phlegethontis). Western North American Naturalist 66:434-440.

Bottrell, H.H., 1975. Relationship Between Temperature and Duration of Egg Development in Some Epiphytic Cladocera and Copepoda From River Thames, Reading, With a Discussion of Temperature Functions. Oecologia 18:63-84.

Bourque, C.P.A. and J.H. Pomeroy, 2001. Effects of Forest Harvesting on Summer Stream Temperatures in New Brunswick, Canada: An Inter-Catchment, Multiple-Year Comparison. Hydrology and Earth System Sciences 5:599-613.

Brannon, E.L., M.S. Powell, T.P. Quinn, and A. Talbot, 2004. Population Structure of Columbia River Basin Chinook Salmon and Steelhead Trout. Reviews in Fisheries Science 12:99-232.

Brett, J.R., 1979. Environmental Factors and Growth. In: Fish Physiology, W.S. Hoar, D.J. Randall, and J.R. Brett (Editors). Academic Press, New York, New York, pp. 599-675.

Broadmeadow, S. and T.R. Nisbet, 2004. The Effects of Riparian Forest Management on the Freshwater Environment: A Literature Review of Best Management Practice. Hydrology and Earth System Sciences 8:286-305.

Brown, J.H., J.F. Gillooly, A.P. Allen, V.M. Savage, and G.B. West, 2004. Toward a Metabolic Theory of Ecology. Ecology 85:1771-1789.

Brown, L.E., A.M. Milner, and D.M. Hannah, 2007. Groundwater Influence on Alpine Stream Ecosystems. Freshwater Biology 52:878-890.

Buchanan, J.A., B.A. Stewart, and B.R. Davies, 1988. Thermal-Acclimation and Tolerance to Lethal High-Temperature in the Mountain Stream Amphipod Paramelita-Nigroculus (Barnard). Comparative Biochemistry and Physiology a – Physiology 89:425-431.

Burkholder, B., G.E. Grant, R. Haggerty, T. Khangaonkar, and P.J. Wampler, 2008. Influence of Hyporheic Flow and Geomorphology on Temperature of a Large, Gravel-bed River, Clackamas River, Oregon, USA. Hydrological Processes 22:941-953.

Caissie, D., 2006. The Thermal Regime of Rivers: A Review. Freshwater Biology 51:1389-1406.

Carveth, C.J., A.M. Widmer, S.A. Bonar, and J.R. Simms, 2007. An Examination of the Effects of Chronic Static and Fluctuating Temperature on the Growth and Survival of Spikedace, Meda Fulgida, With Implications for Management. Journal of Thermal Biology 32:102-108.

Clark, E., B.W. Webb, and M. Ladle, 1999. Microthermal Gradients and Ecological Implications in Dorset Rivers. Hydrological Processes 13:423-438.

Clarke, A., 2006. Temperature and the Metabolic Theory of Ecology. Functional Ecology 20:405-412.

Cossins, A.R. and K. Bowler, 1987. Temperature Biology of Animals. Chapman and Hall, London, United Kingdom.

Coutant, C.C., 1977. Compilation of Temperature Preference Data. Journal of the Fisheries Research Board of Canada 34:739-745.

Crisp, D.T., 1981. A Desk Study of the Relationship Between Temperature and Hatching Time for the Eggs of 5 Species of Salmonid Fishes. Freshwater Biology 11:361-368.

Crozier, L. and R.W. Zabel, 2006. Climate Impacts at Multiple Scales: Evidence for Differential Population Responses in Juvenile Chinook Salmon. Journal of Animal Ecology 75:1100-1109.

Danehy, R.J., C.G. Colson, K.B. Parrett, and S.D. Duke, 2005. Patterns and Sources of Thermal Heterogeneity in Small Mountain Streams Within a Forested Setting. Forest Ecology and Management 208:287-302.

Dunham, J.B., A.E. Rosenberger, C.H. Luce, and B.E. Rieman, 2007. Influences of Wildfire and Channel Reorganization on Spatial and Temporal Variation in Stream Temperature and the Distribution of Fish and Amphibians. Ecosystems 10:335-346.

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. Obrien, H.G. Stefany, M. Hondzo, and R.M. Scheller, 1995. A Field Information-Based System for Estimating Fish Temperature Tolerances. Fisheries 20:10-18.

Ebersole, J.L., W.J. Liss, and C.A. Frissell, 2001. Relationship Between Stream Temperature, Thermal Refugia and Rainbow Trout Oncorhynchus Mykiss Abundance in Arid-Land Streams in the Northwestern United States. Ecology of Freshwater Fish 10:1-10.

Ebersole, J.L., W.J. Liss, and C.A. Frissell, 2003. Cold Water Patches in Warm Streams: Physicochemical Characteristics and the Influence of Shading. Journal of the American Water Resources Association 39:355-368.

Elliott, J.M. and M.A. Hurley, 1997. A Functional Model for Maximum Growth of Atlantic Salmon Parr, Salmo Salar, From Two Populations in Northwest England. Functional Ecology 11:592-603.

Enders, G. and R. Wagner, 1996. Mortality of Apatania Fimbriata (Insecta: Trichoptera) During Embryonic, Larval and Adult Life Stages. Freshwater Biology 36:93-104.

Farrell, J.M., J.V. Mead, and B.A. Murry, 2006. Protracted Spawning of St Lawrence River Northern Pike (Esox Lucius): Simulated Effects on Survival, Growth, and Production. Ecology of Freshwater Fish 15:169-179.

Fernald, A.G., D.H. Landers, and P.J. Wigington, 2006. Water Quality Changes in Hyporheic Flow Paths Between a Large Gravel Bed River and Off-Channel Alcoves in Oregon, USA. River Research and Applications 22:1111-1124.

Ferrari, M.R., J.R. Miller, and G.L. Russell, 2007. Modeling Changes in Summer Temperature of the Fraser River During the Next Century. Journal of Hydrology 342:336-346.

Fitter, A. and R. Hay, 2002. Environmental Physiology of Plants (Third Edition). Academic Press, London, United Kingdom.

Frutiger, A., 1996. Embryogenesis of Dinocras Cephalotes, Perla Grandis and P-Marginata (Plecoptera: Perlidae) in Different Temperature Regimes. Freshwater Biology 36:497-508.

Giller, P.S. and B. Malmqvist, 1998. The Biology of Streams and Rivers. Oxford University Press, Oxford, United Kingdom.

Goniea, T.M., M.L. Keefer, T.C. Bjornn, C.A. Peery, D.H. Bennett, and L.C. Stuehrenberg, 2006. Behavioral Thermoregulation and Slowed Migration by Adult Fall Chinook Salmon in Response to High Columbia River Water Temperatures. Transactions of the American Fisheries Society 135:408-419.

Hardison, E.C., M.A. O'Driscoll, J.P. DeLoatch, R.J. Howard, and M.M. Brinson, 2009. Urban Land Use, Channel Incision, and Water Table Decline Along Coastal Plain Streams, North Carolina(1). Journal of the American Water Resources Association 45:1032-1046.

Hauer, F.R. and A.C. Benke, 1991. Rapid Growth of Snag-Dwelling Chironomids in a Blackwater River – The Influence of Temperature and Discharge. Journal of the North American Benthological Society 10:154-164.

Hendry, A.P., J.E. Hensleigh, and R.R. Reisenbichler, 1998. Incubation Temperature, Developmental Biology, and the Divergence of Sockeye Salmon (Oncorhynchus Nerka) Within Lake Washington. Canadian Journal of Fisheries and Aquatic Sciences 55:1387-1394.

Hester, E.T., M.W. Doyle, and G.C. Poole, 2009. The Influence of In-Stream Structures on Summer Water Temperatures Via Induced Hyporheic Exchange. Limnology and Oceanography 54:355-367.

Hill, D.K. and J.J. Magnuson, 1990. Potential Effects of Global Climate Warming on the Growth and Prey Consumption of Great-Lakes Fish. Transactions of the American Fisheries Society 119:265-275.

Hill, R.W., G.A. Wyse, and M. Anderson, 2004. Animal Physiology. Sinauer Associates, Inc., Sunderland, Massachusetts.

Hokanson, K.E.F., C.F. Kleiner, and T.W. Thorslund, 1977. Effects of Constant Temperatures and Diel Temperature-Fluctuations on Specific Growth and Mortality-Rates and Yield of Juvenile

Rainbow-Trout, Salmo-Gairdneri. Journal of the Fisheries Research Board of Canada 34:639-648.

Huey, R.B. and J.G. Kingsolver, 1989. Evolution of Thermal Sensitivity of Ectotherm Performance. Trends in Ecology & Evolution 4:131-135.

Hughes, N.F. and T.C. Grand, 2000. Physiological Ecology Meets the Ideal-Free Distribution: Predicting the Distribution of Size-Structured Fish Populations Across Temperature Gradients. Environmental Biology of Fishes 59:285-298.

Hulse, D., A. Branscomb, C. Enright, S. Gregory, and R. Wildman, 2007. Linking Cold-Water Refuges Into a Biologically Effective Network in the Southern Willamette River Floodplain: Outlining Key Locations and Knowledge Gaps. Mid-Willamette Valley Council of Governments, Portland, Oregon.

Humpesch, U.H. and J.M. Elliott, 1980. Effect of Temperature on the Hatching Time of Eggs of 3 Rhithrogena Spp (Ephemeroptera) From Austrian Streams and an English Stream and River. Journal of Animal Ecology 49:643-661.

Hunter, J.E. and F.L. Schmidt, 1990. Methods of Meta-Analysis: Correcting Error and Bias in Research Findings. Sage Publications, Newbury Park, California.

Hurst, T.P. and D.O. Conover, 1998. Winter Mortality of Young-of-the-Year Hudson River Striped Bass (Morone saxatilis): Size-Dependent Patterns and Effects on Recruitment. Canadian Journal of Fisheries and Aquatic Sciences 55:1122-1130.

Huryn, A.D., 1996. Temperature-Dependent Growth and Life Cycle of Deleatidium (Ephemeroptera: Leptophlebiidae) in Two High-Country Streams in New Zealand. Freshwater Biology 36:351-361.

Johnson, S.L., 2004. Factors Influencing Stream Temperatures in Small Streams: Substrate Effects and a Shading Experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:913-923.

Johnstone, H.C. and F.J. Rahel, 2003. Assessing Temperature Tolerance of Bonneville Cutthroat Trout Based on Constant and Cycling Thermal Regimes. Transactions of the American Fisheries Society 132:92-99.

Jonsson, B., T. Forseth, A.J. Jensen, and T.F. Naesje, 2001. Thermal Performance of Juvenile Atlantic Salmon, Salmo Salar L. Functional Ecology 15:701-711.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K.P. Gallo, J. Lindsay, R.J. Charlson, and T.C. Peterson, 1993. A New Perspective on Recent Global Warming – Asymmetric Trends of Daily Maximum and Minimum Temperature. Bulletin of the American Meteorological Society 74:1007-1023.

Kentucky Environmental and Public Protection Cabinet, 2008. Final 2008 Integrated Report to Congress on the Condition of Water Resources in Kentucky, Volume II. 303(d) List of Surface Waters. Frankfort, Kentucky.

Kinouchi, T., H. Yagi, and M. Miyamoto, 2007. Increase in Stream Temperature Related to Anthropogenic Heat Input From Urban Wastewater. Journal of Hydrology 335:78-88.

Knispel, S., M. Sartori, and J.E. Brittain, 2006. Egg Development in the Mayflies of a Swiss Glacial Floodplain. Journal of the North American Benthological Society 25:430-443.

Koehle, J.J. and I.R. Adelman, 2007. The Effects of Temperature, Dissolved Oxygen, and Asian Tapeworm Infection on Growth and Survival of the Topeka Shiner. Transactions of the American Fisheries Society 136:1607-1613.

Lackey, R.T., D.H. Lach, and S.L. Duncan, 2006. Salmon 2100: The Future of Wild Pacific Salmon. American Fisheries Society, Bethesda, Maryland.

Lappalainen, J., H. Dorner, and K. Wysujack, 2003. Reproduction Biology of Pikeperch (Sander Lucioperca (L.)) – A Review. Ecology of Freshwater Fish 12:95-106.

Leach, S.D. and E.D. Houde, 1999. Effects of Environmental Factors on Survival, Growth, and Production of American Shad Larvae. Journal of Fish Biology 54:767-786.

LeBlanc, R.T., R.D. Brown, and J.E. FitzGibbon, 1997. Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams. Journal of Environmental Management 49:445-469.

Leopold, L.B., 1968. Hydrology for Urban Land Planning. A Guidebook on the Hydrologic Effects of Urban Land Use. U.S. Geological Survey Circular 554:1-18.

Loheide, S.P. and S.M. Gorelick, 2006. Quantifying Stream-Aquifer Interactions Through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories. Environmental Science & Technology 40:3336-3341.

Lomolino, M.V., B.R. Riddle, and J.H. Brown, 2006. Biogeography (Third Edition). Sinauer Associates, Inc., Sunderland, Massachusetts.

Lynch, J.A., G.B. Rishel, and E.S. Corbett, 1984. Thermal Alteration of Streams Draining Clear-Cut Watersheds – Quantification and Biological Implications. Hydrobiologia 111:161-169.

Magoulick, D.D. and M.A. Wilzbach, 1998. Effect of Temperature and Macrohabitat on Interspecific Aggression, Foraging Success, and Growth of Brook Trout and Rainbow Trout Pairs in Laboratory Streams. Transactions of the American Fisheries Society 127:708-717.

McKie, B.G., P.S. Cranston, and R.G. Pearson, 2004. Gondwanan Mesotherms and Cosmopolitan Eurytherms: Effects of Temperature on the Development and Survival of Australian Chironomidae (Diptera) From Tropical and Temperate Populations. Marine and Freshwater Research 55:759-768.

McKie, B.G. and R.G. Pearson, 2006. Environmental Variation and the Predator-Specific Responses of Tropical Stream Insects: Effects of Temperature and Predation on Survival and Development of Australian Chironomidae (Diptera). Oecologia 149: 328-339.

McMahon, T.E., A.V. Zale, F.T. Barrows, J.H. Selong, and R.J. Danehy, 2007. Temperature and Competition Between Bull Trout and Brook Trout: A Test of the Elevation Refuge Hypothesis. Transactions of the American Fisheries Society 136: 1313-1326.

Millenium-Ecosystem-Assessment, 2005. Ecosystems and Human Well-Being. Island Press, Washington, D.C.

Mochizuki, S., Y. Kayaba, and K. Tanida, 2006. Larval Growth and Development in the Caddisfly Cheumatopsyche Brevilineata Under Natural Thermal Regimes. Entomological Science 9:129-136.

Mohseni, O., T.R. Erickson, and H.G. Stefan, 1999. Sensitivity of Stream Temperatures in the United States to Air Temperatures Projected Under a Global Warming Scenario. Water Resources Research 35:3723-3733.

Moore, R.D., D.L. Spittlehouse, and A. Story, 2005. Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review. Journal of the American Water Resources Association 41:813-834.

Morrison, J., M.C. Quick, and M.G.G. Foreman, 2002. Climate Change in the Fraser River Watershed: Flow and Temperature Projections. Journal of Hydrology 263:230-244.

Nichelmann, M., 1983. Some Characteristics of the Biological Optimum Temperature. Journal of Thermal Biology 8:69-71.

Nielsen, J.L., T.E. Lisle, and V. Ozaki, 1994. Thermally Stratified Pools and Their Use by Steelhead in Northern California Streams. Transactions of the American Fisheries Society 123:613-626.

Ojanguren, A.F., F.G. Reyes-Gavilan, and F. Brana, 2001. Thermal Sensitivity of Growth, Food Intake and Activity of Juvenile Brown Trout. Journal of Thermal Biology 26:165-170.

Oregon Department of Environmental Quality, 2006. Water Quality Assessment Database. http://www.deq.state.or.us/wq/assessment/rpt0406/search.asp#db.in, accessed January 31, 2011.

Pedersen, N.L. and K. Sand-Jensen, 2007. Temperature in Lowland Danish Streams: Contemporary Patterns, Empirical Models and Future Scenarios. Hydrological Processes 21:348-358.

Pilgrim, J.M., X. Fang, and H.G. Stefan, 1998. Stream Temperature Correlations With Air Temperatures in Minnesota: Implications for Climate Warming. Journal of the American Water Resources Association 34:1109-1121.

Pockl, M., 1992. Effects of Temperature, Age and Body Size on Molting and Growth in the Fresh-Water Amphipods Gammarus-Fossarum and Gammarus-Roeseli. Freshwater Biology 27:211-225.

Poole, G.C. and C.H. Berman, 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation. Environmental Management 27:787-802.

Pritchard, G. and J. Zloty, 1994. Life-Histories of 2 Ameletus Mayflies (Ephemeroptera) in 2 Mountain Streams – The Influence of Temperature, Body-Size, and Parasitism. Journal of the North American Benthological Society 13:557-568.

Reynolds, S.K. and A.C. Benke, 2005. Temperature-Dependent Growth Rates of Larval Midges (Diptera: Chironomidae) From a Southeastern US Stream. Hydrobiologia 544:69-75.

Rounds, S., 2007. Temperature Effects of Point Sources, Riparian Shading, and Dam Operations on the Willamette River, Oregon. Scientific Investigations Report 2007-5185. U.S. Geological Survey, Reston, Virginia.

Rutherford, J.C., N.A. Marsh, P.M. Davies, and S.E. Bunn, 2004. Effects of Patchy Shade on Stream Water Temperature: How Quickly Do Small Streams Heat and Cool? Marine and Freshwater Research 55:737-748.

Salas, M. and D. Dudgeon, 2001. Laboratory and Field Studies of Mayfly Growth in Tropical Asia. Archiv Fur Hydrobiologie 153:75-90.

Schiemer, F., H. Keckeis, and E. Kamler, 2003. The Early Life History Stages of Riverine Fish: Ecophysiological and Environmental Bottlenecks. Comparative Biochemistry and Physiology a – Molecular and Integrative Physiology 133:439-449.

Secor, D.H. and E.D. Houde, 1995. Temperature Effects on the Timing of Striped Bass Egg-Production, Larval Viability, and Recruitment Potential in the Patuxent River (Chesapeake Bay). Estuaries 18:527-544.

Selong, J.H., T.E. McMahon, A.V. Zale, and F.T. Barrows, 2001. Effect of Temperature on Growth and Survival of Bull Trout, With Application of an Improved Method for Determining Thermal Tolerance in Fishes. Transactions of the American Fisheries Society 130:1026-1037.

Sherman, B., C.R. Todd, J.D. Koehn, and T. Ryan, 2007. Modelling the Impact and Potential Mitigation of Cold Water Pollution on Murray Cod Populations Downstream of Hume Dam, Australia. River Research and Applications 23:377-389.

Smith, K., 1972. River Water Temperatures – An Environmental Review. Scottish Geographical Magazine 88:211-220.

Soderstrom, O., 1988. Effects of Temperature and Food Quality on Life-History Parameters in Parameletus-Chelifer and P-Minor (Ephemeroptera) – A Laboratory Study. Freshwater Biology 20:295-303.

Story, A., R.D. Moore, and J.S. Macdonald, 2003. Stream Temperatures in Two Shaded Reaches Below Cutblocks and Logging Roads: Downstream Cooling Linked to Subsurface Hydrology. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 33:1383-1396.

Sutcliffe, D.W., T.R. Carrick, and L.G. Willoughby, 1981. Effects of Diet, Body Size, Age and Temperature on Growth Rates in the Amphipod Gammarux Pulex. Freshwater Biology 11: 183-214.

Sutcliffe, J., 1977. Plants and Temperature. The Camelot Press, Ltd., Southampton, United Kingdom.

Sweeney, B.W. and R.L. Vannote, 1978. Size Variation and Distribution of Hemimetabolous Aquatic Insects – 2 Thermal-Equilibrium Hypotheses. Science 200:444-446.

Takeshita, N., I. Ikeda, N. Onikura, M. Nishikawa, S. Nagata, S. Matsui, and S. Kimura, 2005. Growth of the Fourspine Sculpin Cottus Kazika in the Gonokawa River, Japan, and Effects of Water Temperature on Growth. Fisheries Science 71:784-790.

Todd, C.R., T. Ryan, S.J. Nicol, and A.R. Bearlin, 2005. The Impact of Cold Water Releases on the Critical Period of Post-Spawning Survival and Its Implications for Murray Cod (Maccullochella Peelii Peelii): A Case Study of the Mitta Mitta River, Southeastern Australia. River Research and Applications 21:1035-1052.

Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh, 1999. Multiscale Thermal Refugia and Stream Habitat Associations of Chinook Salmon in Northeastern Oregon. Ecological Applications 9:301-319.

USEPA, 1999. Rapid Bioassessment Protocols for Use in Wadeable Streams and Rivers. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. EPA 841-B-99-002.

Van Eenennaam, J.P., J. Linares-Casenave, X. Deng, and S.I. Doroshov, 2005. Effect of Incubation Temperature on Green Sturgeon Embryos, Acipenser Medirostris. Environmental Biology of Fishes 72:145-154.

Vernier, J.M., 1969. Table Chronologique du Development Embryonaire de la Truite arc-en-Ciel, Salmo Gairdneri. Annales d'Embryologie et de Morphogenese 2:495-520.

Wagner, C.P. and D.H. Wahl, 2007. Evaluation of Temperature-Selection Differences Among Juvenile Muskellunge Originating From Different Latitudes. Environmental Biology of Fishes 79:85-98.

Walther, G.R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein, 2002. Ecological Responses to Recent Climate Change. Nature 416:389-395.

Ward, J.V., 1985. Thermal-Characteristics of Running Waters. Hydrobiologia 125:31-46.

Webb, B.W., 1996. Trends in Stream and River Temperature. Hydrological Processes 10:205-226.

Whitledge, G.W. and C.F. Rabeni, 2002. Maximum Daily Consumption and Respiration Rates at Four Temperatures for Five Species of Crayfish From Missouri, USA (Decapoda, Orconectes spp.). Crustaceana 75:1119-1132.

Zwick, P., 1996. Variable Egg Development of Dinocras spp (Plecoptera, Perlidae) and the Stonefly Seed Bank Theory. Freshwater Biology 35:81-99.